REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
16-12-2010	Final Report	1-Sep-2006 - 31-Aug-2010

4. TITLE AND SUBTITLE
Cortical Mechanisms of Multi-step Action Planning

5a. CONTRACT NUMBER
W911NF-06-1-0381

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
6620V0

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
49581-LS.2

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Our project seeks to understand the changes in behavior and brain that accompany the development of expertise in the telecontrol of tools and devices. Particular emphasis is placed on the control of multi-step actions in which ongoing behavior must be adjusted in anticipation of forthcoming task demands. These anticipatory adjustments to behavior reflect the use of internal representations. We are using functional magnetic resonance imaging (fMRI) and behavioral measures (kinematics) to investigate the changes that occur in these internal representations as

15. SUBJECT TERMS
fMRI, motor planning, tool use, telecontrol

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Scott Frey
UU	UU	UU	UU		19b. TELEPHONE NUMBER 541-346-4953

Report Title

Cortical Mechanisms of Multi-step Action Planning

ABSTRACT

Our project seeks to understand the changes in behavior and brain that accompany the development of expertise in the telecontrol of tools and devices. Particular emphasis is placed on the control of multi-step actions in which ongoing behavior must be adjusted in anticipation of forthcoming task demands. These anticipatory adjustments to behavior reflect the use of internal representations. We are using functional magnetic resonance imaging (fMRI) and behavioral measures (kinematics) to investigate the changes that occur in these internal representations as operators develop expertise in controlling a remotely located robotic arm for goal-oriented reaching, grasping and object manipulation. Results of this work will have widespread implications for the increasingly commonplace situations in modern combat and telemedical environments where individuals must plan and operate a wide variety of devices remotely, under highly variable contexts, and with limited sensory feedback.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Arbib, M. A., Bonaiuto, J. B., Jacobs, S., & Frey, S. H. (2009). Tool use and the distalization of the end-effector. Psychol Res, 73(4), 441-462. doi: 10.1007/s00426-009-0242-2

Jacobs, S., Danielmeier, C., & Frey, S. H. (2010). Human anterior intraparietal and ventral premotor cortices support representations of grasping with the hand or a novel tool. J Cogn Neurosci, 22(11), 2594-2608. doi: 10.1162/jocn.2009.21372

Frey, S.H. "Forecasting the long-range consequences of manual and tool use actions: neurophysiological, behavioral and computational considerations." In F. Danion, F. & M. Latash (Eds). Progress in Motor Control VII.

Number of Papers published in peer-reviewed journals: 3.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Jacobs,S., Danielmeier, C., & Frey, S.H. "Effector-independent action representations in anterior intra-parietal sulcus: evidence from tool use." Presented at the Annual Meeting of the Society for Neuroscience. Washington, D.C. (November, 2008).

Marangon, M., Jacobs, S.H., & Frey, S.H. "Anticipatory effects of multi-step action planning: an fMRI study." Annual Meeting of the Cognitive Neuroscience Society. San Francisco. (March, 2009).

Jacobs, S., & Frey, S.H. "Neural substrates of the integration of a tool into the visual representation of the hand." Progress in Motor Control VII. Marseille, France (July, 2009).

Frey, S.H. "Experience-dependent changes in brain organization associated with the use of tools." Progress in Motor Control VII. Marseille, France (July, 2008).

Hansen, M., Marchal, N., & Frey, S.H. "Parieto-premotor contributions to the planning and/or execution of reaching or grasping movements studied in humans with fMRI." Paper to be presented at the Annual Meeting of the Society for Neuroscience. San Diego. (November, 2010).

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 5

(d) Manuscripts

Marangon, M., Jacobs, S., & Frey, S.H. (submitted). "Context-sensitivity of grasp representations in human rostral inferior parietal lobule."

Miller-Martin, K., Jacobs, S., and Frey, S.H. (submitted). "Handedness-related differences in contributions of anterior intraparietal and ventral premotor cortices to feed-forward grip selection involving the hands or a recently mastered tool."

Number of Manuscripts: 2.00

Patents Submitted

Patents Awarded

Awards

Member Motor Function, Speech and Rehabilitation (MFSR) NIH Study Section, Oct. 2008 – June 2012

Eugene Michels Research Forum Speaker, American Physical Therapy Assn., 2010.

Section Leader (Basic Science of Action): James S. McDonnell Foundation's Evidence-based Rehabilitation Project, 2008 - present

Fund for Faculty Excellence Award, University of Oregon, 2008
Kavli Frontiers of Science Session Chair, National Academy of Sciences, 2007

Kavli Frontiers of Science Fellow, National Academy of Sciences, 2006
Posner/Boies Faculty Research Award, 2006

Graduate Students

NAME	PERCENT_SUPPORTED
Loehle-Conger, Evan	0.49
FTE Equivalent:	**0.49**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Stephane Jacobs	1.00
Mattia Marangon	1.00
Marc Hansen	1.00
Kristen Macuga	1.00
FTE Equivalent:	**4.00**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Evan Loehle-Conger	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Total Number:	

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Our project sought to understand the changes in behavior and brain that accompany the development of expertise in the telecontrol of tools and devices. Particular emphasis was placed on the control of multi-step actions in which ongoing behavior must be adjusted in anticipation of forthcoming task demands. These anticipatory adjustments to behavior reflect the use of internal representations. We used functional magnetic resonance imaging (fMRI) and behavioral measures to investigate the changes that occur in these internal representations as operators develop expertise in controlling manual tools and a remotely located robotic arm for goal-oriented reaching, grasping and object manipulation. Results of this work may have widespread implications for the increasingly commonplace situations in modern combat and telemedical environments where individuals must plan and operate a wide variety of devices remotely, under highly variable contexts, and with limited sensory feedback.

As summarized below, and in the attached figures, we have pursued four general objectives during the past year.

Objective 1: Characterization of the behavioral and neural signatures of anticipatory movement selection. The way that we choose to grasp an object (e.g., over- vs. under-hand) depends on sensory information concerning the state of the body (e.g., current posture) and the target object (e.g., location, orientation), as well as anticipation of forthcoming task demands (e.g., intended rotation of the target object). For instance, when grasping a handle with the intention to rotate it, participants may select a less-comfortable grip in order to end in a more comfortable posture (Rosenbaum & Jorgensen, 1990). Are such anticipatory effects, evident in multi-step actions, the result of feed forward (predictive) mechanisms that contribute more generally to motor control? Event-related fMRI was used to ask this question in 15 healthy, right-handed adults. Participants were required to select the most comfortable way (over- vs. under-hand) to grasp a handle using either hand with the intention of simply grasping the handle (NO-ROTATION) or rotating it 90^0 clockwise or counterclockwise (ROTATION). . Responses indicated which end of the handle the thumb would be on, and no overt movements were made. As expected if they were accurately anticipating forthcoming task demands participants were more likely to adopting an underhand grip in ROTATION vs, NO-ROTATION condition. Consistent with earlier work, grip selection planning in the NO-ROTATION condition was associated with increased activity in inferior frontal and dorsal premotor cortices, pre-supplementary motor area, intraparietal sulci and lateral cerebellum. As shown in **Figure 1**, planning in the ROTATION condition evoked additional increases in activity within these very same brain regions. These findings are consistent with the hypothesis that the same brain regions underlie anticipatory planning motor planning across multiple timescales. These results are currently under revision for resubmission to the *Journal of Neurophysiology.*

Objective 2: Development of an MRI-compatible system to investigate internal representations underlying telecontrol of a robotic arm. Our first pass at a glove controller mapped individual cyber-glove sensors to servos on the robot (**Figure 2)**. Controlling the robot this way was confusing and difficult to master. Furthermore, once the robot was in the desired position the participant's hand had to be held perfectly steady while, for example, opening or closing the gripper or the robot would move.

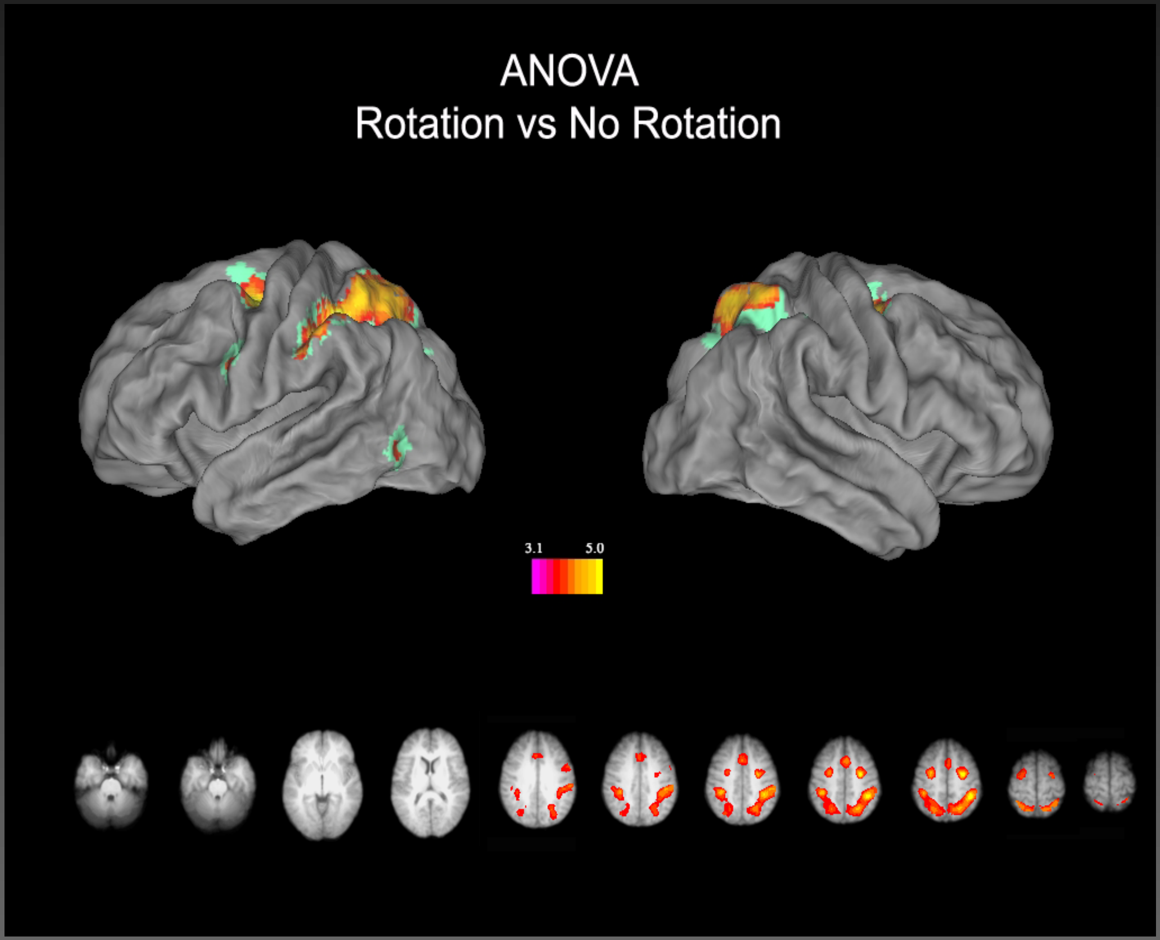
We came up with two improvements to the initial system and have continued to test these. The first was to implement a "joystick" mode in the glove controller software. In this mode, only the ends of the range of movement for a joint associated with a sensor cause the robot to move. The center of the joint movement range is a "dead zone", allowing the participant to maintain her hand in a neutral position while keeping the robot from moving. The second improvement addresses the difficulty in moving the robot by controlling individual joints. Instead, we implemented an inverse kinematics solution where glove movements control the position of the robot's end effector in space. The robot's servo values are then back-calculated from the desired end effector position. Since one of our aims is to allow live control of the robot, we needed to make our calculations as fast as possible. Therefore we implemented a geometric inverse kinematics solution rather than an iterative one. For this calculation we had the option of letting the participant use Cartesian, cylindrical, or spherical coordinates. While Cartesian coordinates would probably be more familiar to the average participant, the types well as the calculations involved, we decided to keep the gripper parallel to the ground. With this added constraint, the cylindrical coordinate system ended up making the most sense. We are presently pilot testing a learning paradigm that will enable us to track neural correlates of the development of telecontrol expertise using this system.

Objective 3: Parieto-premotor contributions to the planning and/or execution of reaching or grasping movements studied in humans with fMRI. There is considerable evidence implicating the anterior intraparietal area (AIP) and ventral premotor cortex (F5) of macaques in sensori-motor transformations for grasp. Studies of visually-guided grasping in humans consistently detect activation near the junction of the anterior intraparietal and postcentral sulci (aIPS). Interesting exceptions include tasks in which participants grasp under open-loop conditions (i.e., without visual feedback, Binkofski et al., 1999), and when they plan grasping actions while remaining still (Jacobs et al., 2009). These findings raise the possibility that vPMC may play a greater role in feed-forward (predictive) control, while aIPS is more involved in feedback processing. To address this question, we used a rapid, event-related fMRI paradigm to distinguish activity involved in the planning vs. execution phases of reaching and grasping movements in 18 healthy right-handed adults.

At the onset of each trial an instructional cue indicated whether the forthcoming movement would involve reaching or grasping. This was followed by a variable duration delay period (3 – 4s). Trials were separated by a fixed duration intertrial interval (0.5s), and one third of trials within the run consisted of null events. Onset of the visual display served as the movement cue. Subjects then reached toward or grasped a 25 x 25 x 50mm wooden block with their right hands. In the grasp condition, the block was picked up, transported laterally and placed in a 50mm diameter, circular opening. In the reach condition, the fingertips were kept in contact with each other as the subject touched the top of the block and then moved the hand over the hole. As expected, the comparison of grasp execution vs. reach execution yielded increased activity in aIPS (**Figure 3)**. Importantly, activity within this functionally-defined region of interest only shows increased activity for reach and grasp execution and not for planning. By contrast, more caudal angular gyrus (ANG) showed significant increases in activity for planning grasping or reaching, but not for execution of either action (**Figure 4**). These findings suggest that the human aIPS may be more heavily involved in sensorimotor control of grasp, while more caudal regions of posterior parietal cortex participate in premovement, feedforward planning of both grasp and reach. This work was presented at the *2010 Meeting of the Society for Neuroscience* and a manuscript is in preparation for submission to a peer-reviewed journal.

Objective 4: fMRI Experiment 1: Responses of the parieto-frontal grasp network to control of telecontrol robot grasping. As summarized in Objective 3 above, there is a network of areas in parietal and premotor cortex that are involved in the internal representation of grasping. Importantly, we showed that these same areas come to code grasping with a novel handheld tool once operators have achieved a level of expertise. Put differently, it appears that these regions code grasping independent of the effector involved. In this initial experiment with the robotic arm, we ask whether, following training, this "grasp" network comes to also represent grasping with a telecontrolled robotic arm. To keep matters simple, the operator was trained to press one button to control the position of the robot (i.e., reach), and another to control movements of the gripper (i.e., grasp). We reasoned that if this parieto-premotor circuit is involved in the control of grasping independent of the effector involved, then telecontrolled grasping will increase activity selectively within these regions. As shown in **Figure 5**, this is what we found. After developing expertise in controlling the robotic arm, participants show engagement of posterior parietal (green arrows) and premotor (blue arrows) regions normally involved in the control of manual reach (left) and grasp (right). This even when the hand movements used to control the robot are simple button presses. This suggests that learning to control remote devices under teleoperational conditions is accomplished within the same circuits that underlie comparable goal directed actions involving one's own body. This is consistent with what was found earlier in this project for use of handheld mechanical tools. We believe that this information may have practical implications for development of training protocols for telecontrol and for enhancement of brain-controlled interfaces. A manuscript is in preparation for submission to a peer-reviewed

Figure 1: Anticipatory Grip Selection



Marangon, Jacobs & Frey, submitted.

Figure 2: fMRI-Compatible Telecontroller

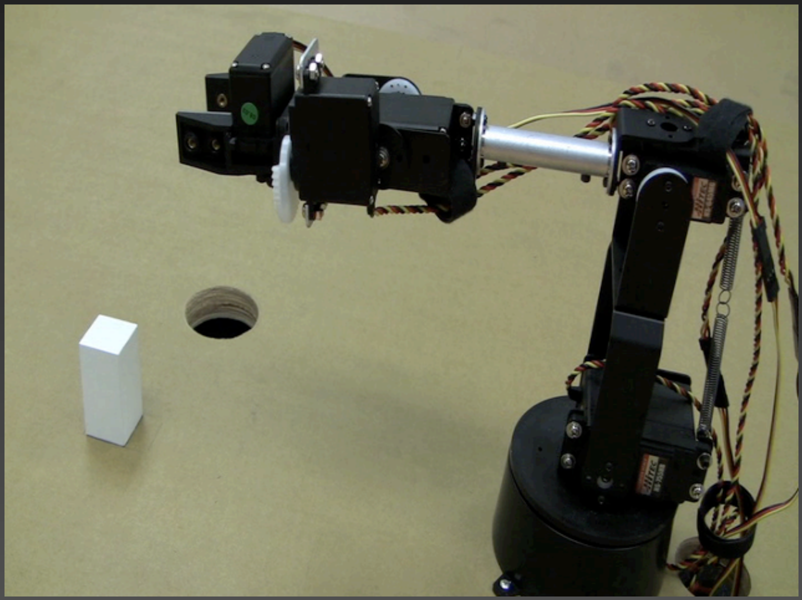


Figure 3: Percent Signal Change in aIPS

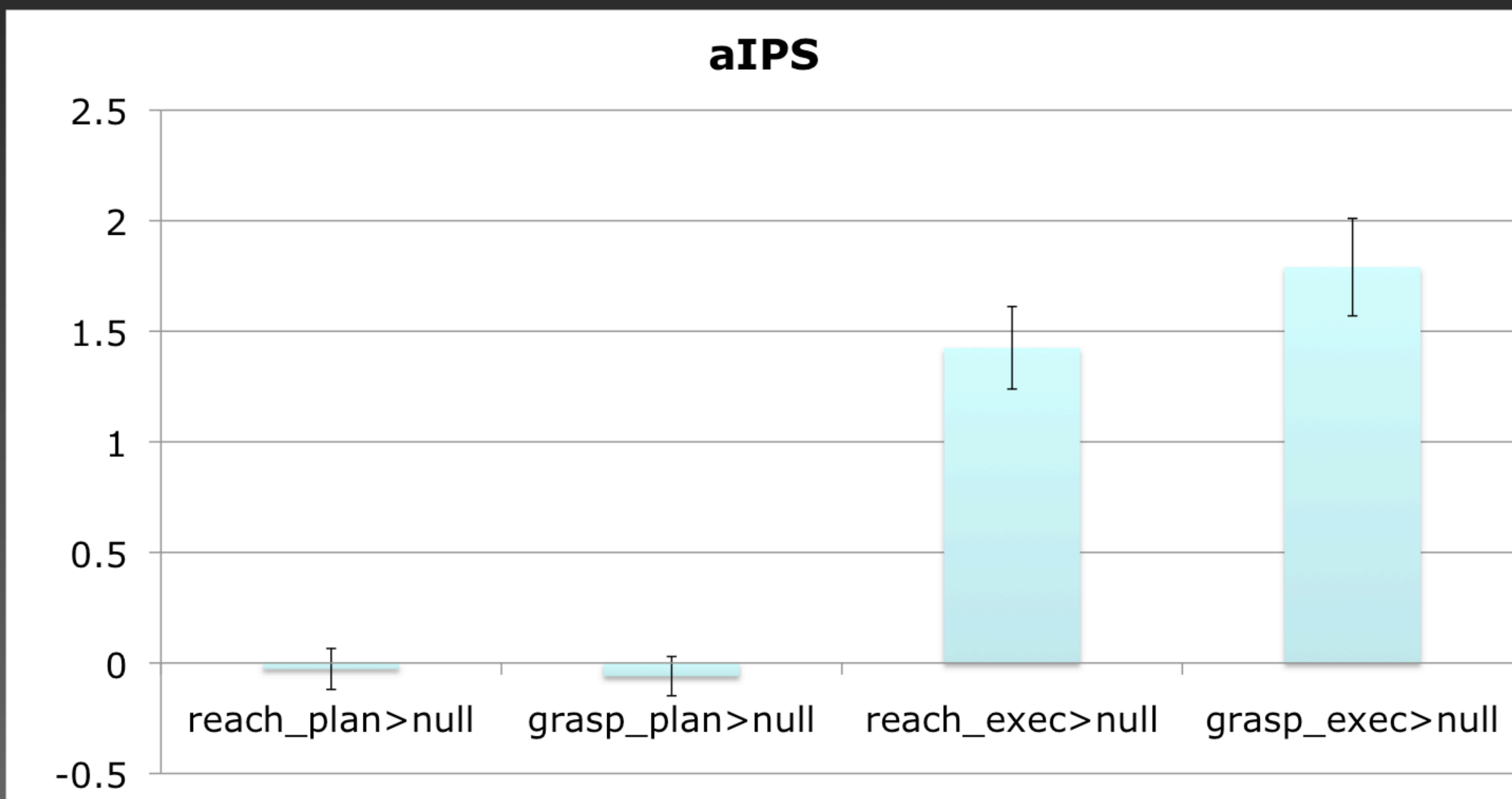


Figure 4: Percent Signal Change in ANG

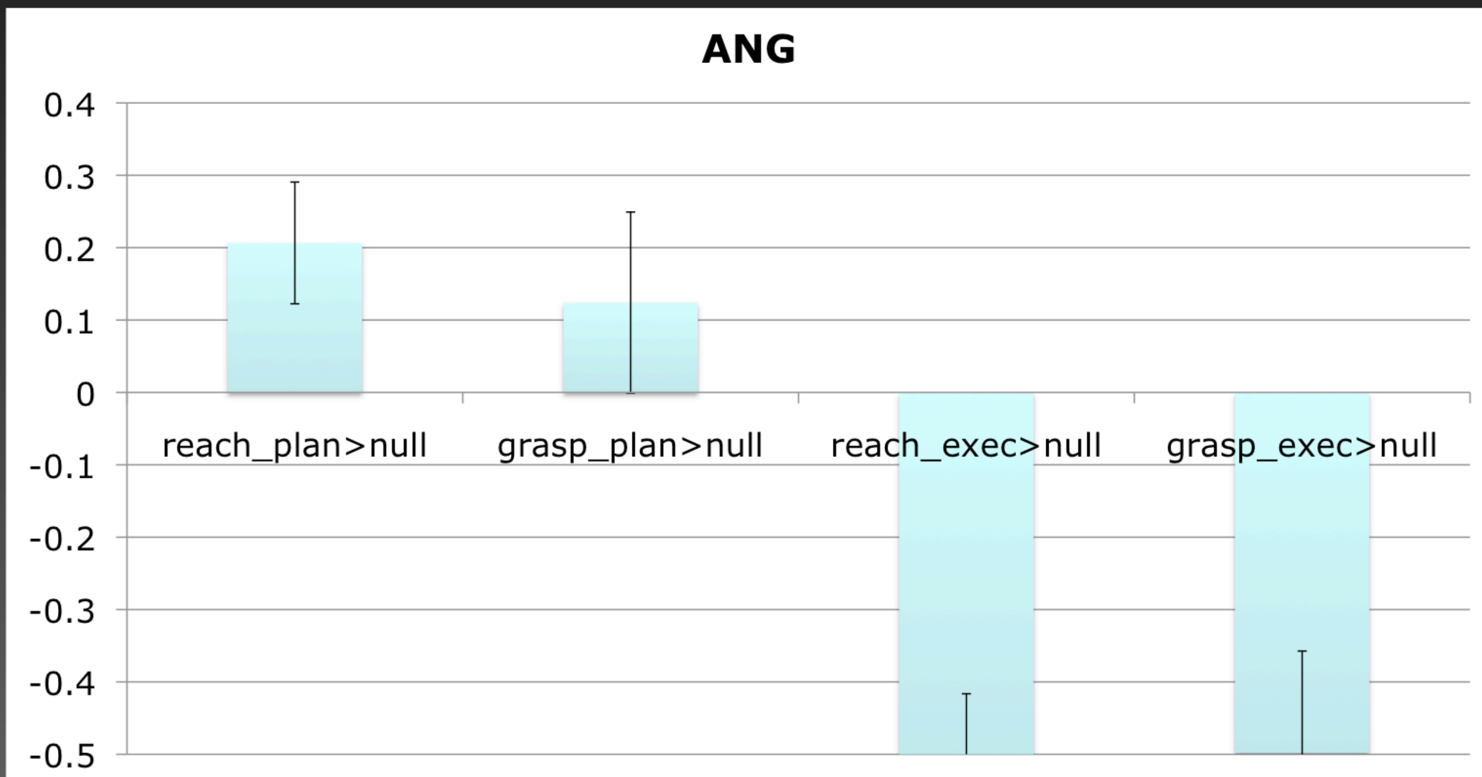
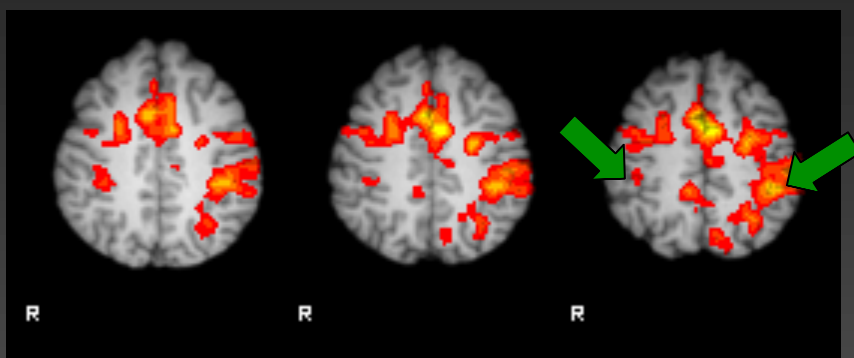
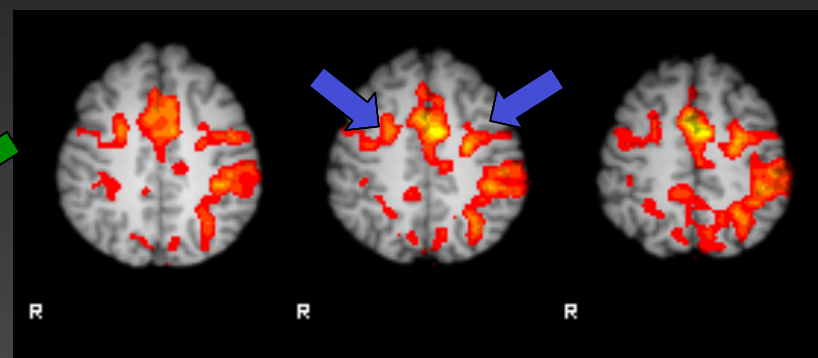


Figure 5: Single Subject Data



Teleoperative reach planning > rest



Teleoperative grasp planning > rest